Title of the Invention

BIOMAGNETIC FIELD MEASURING
METHOD AND APPARATUS

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BACKGROUND OF THE INVENTION

The present invention relates to biomagnetic field measuring method and apparatus for measuring a biomagnetic field generated by a nerve action of brain as well as a myocardial action of heart of a living body by using a plurality of fluxmeters each consisting of a highly sensitive superconducting quantum interference device (SQUID).

In addition to a magnetic field generated by a current dipole, a magnetic field due to a volume current flowing in the living body is enumerated as a biomagnetic field. Measurement of a normal component (B_z : z component in the Cartesian coordinate system or B_r : radius component in the polar coordinate system) is considered to be hardly affected by the volume current. In conventional techniques, the plane of a detection coil connected to a SQUID is disposed in parallel to the body surface to measure B_z or B_r which is a normal component vertical to the body surface. Results of the biomagnetic field measurement are displayed in the form of a temporal change waveform of the measured field component or an isomagnetic field map (contour map) for connecting points at which magnitudes of the magnetic field component measured at desired time points are equal to each other. Various

analysis methods have been proposed which analyze a
magnetic field source participating in generation of the
biomagnetic field from the obtained isomagnetic field curve
and in typical one of them, analysis is carried out by
5 replacing the magnetic field source with a current dipole.

An isomagnetic field map of a normal component
(B_z or B_r) of the magnetic field generated by a current
dipole is of a pattern having a source pole of magnetic
field and a sink pole of magnetic field at positions which
10 are separate from each other from the center where a
magnetic field source (current dipole) is positioned. The
magnitude, position and direction of the magnetic field
source (current dipole) are analyzed in accordance with
magnitudes of magnetic field at the two poles and a
15 distance therebetween.

In a first prior art (H. Hosaka and D. Cohen: J.
Electrocardiology, 9 (4), pp. 426-432 (1976)), a method is
employed for displaying current sources distributed in the
myocardium by using an isomagnetic field map of measured
20 normal component B_z with the aim of promoting visibleness
of direction and intensity of currents in the myocardium
and according to this method, an arrow map is contrived for
expressing a current vector J (x, y) defined by equation
(1) on measuring points by using an arrow. In the
25 following description, Gothic characters are used to
indicate vectors.

$$J(x, y)$$

$$= (\partial B_z(x, y)/\partial y)e_x - (\partial B_z(x, y)/\partial x)e_y \quad \ldots \ (1)$$

In equation (1), e_x designates a unit vector in x direction and e_y designates a unit vector in y direction.

5 This prior art, however, encounters a problem that when a plurality of current sources exist, it is difficult to discriminate the individual current sources from each other on the basis of the isomagnetic field map of normal component B_z.

10   In a second prior art (K. Tukada et al: Review of the Scientific Instruments, 66(10), pp. 5085-5091 (1995)), for the sake of visualizing a plurality of distributed current sources, the normal component (B_z or B_r) is not detected but tangential components B_x and B_y are measured

15 by using a detection coil whose plane is disposed vertically to the body surface. Each of the measured tangential components B_x and B_y is displayed in the form of an isomagnetic field map. The tangential components B_x and B_y measured according to the second prior art are

20 considered to be affected by the volume current but in an isomagnetic field map of two-dimensional vector magnitude B_{xy} obtained by synthesizing B_x and B_y measured at time point t pursuant equation (2), a peak can always be obtained directly above a current dipole and therefore,

25 even when a plurality of current dipoles exist, individual current dipoles can be separated for visualization.

$$|B_{xy}(x, y, t)|$$

$$= \sqrt{\{(B_x(x, y, t))^2 + (B_y(x, y, t))^2\}} \quad \ldots (2)$$

In a third prior art (Y. Yoshida et al: Tenth International Conference on Biomagnetism, Santana Fe, New
5   Mexico, Feb. 17 (1996)), a normal component and two tangential components of a biomagnetic field are detected by using a vector magnetic field sensor consisting of three detection coils having coil planes which are orthogonal to each other, detection results of the magnetic field
10 components are converted in terms of the Cartesian coordinate system to determine Cartesian coordinate system components B_x, B_y and B_z, and an isomagnetic field map of the normal component B_z and an isomagnetic field map of two-dimensional vector magnitude B_{xy} are displayed,
15 respectively.

In a fourth prior art (K. Tsukada et al: Tenth International Conference on Biomagnetism, Santana Fe, New Mexico, Feb. 17 (1996)), two tangential components B_x and B_y of a biomagnetic field are detected and an isomagnetic
20 field map based on $|B_{xy}| = |B_x + B_y|$ is compared with an isomagnetic field map based on a normal component B_z.

Available as diagrams for indicating measurement results of electrical physiological phenomena in a living body are a magnetoencephalogram (MEG) obtained through
25 measurement using a magnetoencephalogram and an electrocardiogram (ECG) obtained through measurement using

an electrocardiograph. In measurements of the electrocardiogram, a body surface potential map for mapping an electrocardiographic figure by using a plurality of electrodes is of a well-known technique. The MEG or the body surface potential map is depicted in the form of an isopotential map for connecting isopotential points.

In a fifth prior art (T. J. Montague et al: Circulation 63, No. 5, pp.1166-1172 (1981)), an isointegral map obtained by integrating a temporal change waveform of an output of each one of a plurality of electrodes over a desired time interval is depicted as a body surface potential map.

In the following description, "biomagnetic field" means "magnetic field generated from a living body", "cardiac magnetic field measurement" means "measurement of a magnetic field generated from the heart", and "cardiac magnetic wavaform" means "waveform indicated by a magnetocardiogram (MCG) obtained through cardiac magnetic field measurement". Further, "encephalic magnetic field measurement" means "measurement of a magnetic field generated from the brain" and "encephalic magnetic waveform" means "waveform indicated by a magnetoencephalogram (MEG) obtained through encephalic magnetic field measurement".

Each of the conventional isomagnetic field maps of the respective components has inherent features. In the presence of a single current dipole, the position,

magnitude and direction of a current source can be analyzed with ease by using the isomagnetic field map of normal component B_z. On the other hand, the isomagnetic field map of two-dimensional vector magnitude B_{xy} obtained from

5   measurement results of tangential components B_x and B_y features that even in the presence of a plurality of current dipoles, individual current dipoles can easily be discriminated from each other. But, for detection of a magnetic field, coils are required to be provided in x and

10 y directions and the number of coils is doubled as compared to detection of only the normal component B_z. In vector measurement for measuring all the components B_x, B_y and B_z, the number of required coils is tripled as compared to detection of only the normal component B_z. Accordingly,

15 the magnetic field sensor consisting of a detection coil and a SQUID is increased in number and in addition, the signal processing circuit and the like are also increased in number, raising a problem that the biomagnetic field measuring system becomes an expensive one. Further, the

20 first prior art is disadvantageous in that arrows are merely indicated on measuring points and detailed distribution states of current sources are hardly discriminated.

From the isomagnetic field map indicated in terms

25 of a biomagnetic field component, the position, magnitude and direction, at a desired time point, of a current source in a living body can be analyzed and detailed information

about changes in position, magnitude and direction of the current source can be known. Conventionally, dynamic changes in various kinds of information pieces are captured by using many figures displayed on or delivered to the

5 apparatus so as to diagnose a disease. In the prior arts, however, many diagrams or maps indicating various kinds of information pieces are needed for diagnosis and abnormality of changes in various kinds of information pieces is known empirically. As will be seen from the above, in the prior

10 arts, the processing of displaying, on a single map, systematic information as to what magnitude of current flows through which portion of a living body and as to which region an abnormal bio-current passes through is not executed. In the case of the body surface potential map,

15 an isointegral technique was reported. This isointegral map was drawn by connecting between the same integral values over a desired time interval (for example, an interval during which waves of Q, R and S are generated and an interval during which S to T waves are generated). The

20 advantage of this isointegral map is that information of the heart can be obtained from only a single electrocardiographic figure. But, in the isopotential map, when the current source in the heart is assumed to be a single current dipole, a figure results disadvantageously

25 in which an positive peak and a negative peak do not exist immediately above the current dipole but exist at a position which is separate from a point immediately above

the current dipole. Further, when the position of the current dipole remains unchanged but the direction of the current dipole changes, the anode and cathode peak positions change, raising a problem that when potential is integrated, correspondence between the current source and the peak of an integral value is impaired. Like the case of the electrocardiogram, mere integration of a component of a biomagnetic field obtained through biomagnetic field measurement faces a problem that the peak position of the biomagnetic field component does not correspond to the position of the current source. Further, with only the isointegral map obtained from the electrocardiogram, because of the individual difference such as the position and size of the internal organs, making it difficult to accurately determine abnormality such as a disease by simply gathering from the isointegral map.

SUMMARY OF THE INVENTION

An object of the present invention is to provide biomagnetic field measuring method and apparatus which can grasp the whole state of a living body portion by using maps which are greatly reduced in number as compared to the maps required in the prior arts.

Another object of the present invention is to provide biomagnetic field measuring method and apparatus which can permit analysis of a magnetic field source by measuring a vertical component B_z of a biomagnetic field without increasing the number of detection coils.

According to the present invention, (1) a biomagnetic field measuring method comprises: a first step of measuring a temporal change of a component of a biomagnetic field generated from a living body by using a plurality of fluxmeters disposed externally of the living body and each including a superconducting quantum interference device (SQUID), the magnetic field component being in a first direction which is vertical to the surface of the living body; a second step of determining a temporal change of a value proportional to a root of square sum of change rates of the first-direction magnetic field component in second and third directions which cross the first direction; a third step of integrating the temporal change of the value obtained in the second step over a predetermined interval to determine an integral value, and a fourth step of displaying the integral value obtained in the third step.

According to the present invention, (2) a biomagnetic field measuring method comprises: a first step of measuring temporal changes of components of a biomagnetic field generated from a living body by using a plurality of fluxmeters disposed externally of the living body and each including a superconducting quantum interference device (SQUID), the magnetic field components being in first and second directions which are parallel to the surface of the living body; a second step of determining a temporal change of a value proportional to a

root of square sum of the first-direction and second-direction magnetic field components; a third step of integrating the temporal change of the value obtained in the second step over a predetermined interval to determine

5   an integral value; and a fourth step of displaying the integral value obtained in the third step.

Specifically, in the biomagnetic field measuring methods (1) and (2) as above, the above integral values are used through interpolation and extrapolation to display an

10   isointegral map for connecting points at which the integral values in the above fourth step are equal to each other, the above third step of integrating the temporal change of the value obtained in the second step over a predetermined interval to determine the integral value is carried out

15   over a plurality of predetermined intervals to determine a plurality of integral values, and computation for determining any of the ratio, the sum or the difference between the plurality of integral values is carried out. In the Cartesian coordinate system (x, y, z), the direction

20   vertical to the body surface is defined as z axis, the first direction is defined as z direction, the second direction is defined as x direction and the third direction is defined as y direction. In the polar coordinate system (r, θ, ϕ), the direction vertical to the body surface is

25   defined as r axis, the first direction is defined as r direction, the second direction is defined as θ direction and the third direction is defined as ϕ direction.

According to the present invention, (1) a biomagnetic field measuring apparatus for measuring biomagnetic field distribution comprises: a plurality of fluxmeters disposed externally of a living body and each

5 including a superconducting quantum interference device (SQUID) for detecting, as a signal, a biomagnetic field generated from the living body; operation processing unit for performing the operation processing of the signal; and display unit for displaying a result of the operation

10 processing. In the biomagnetic field measuring apparatus, the fluxmeters detect a temporal change of a component of a biomagnetic field, the magnetic field component being in a first direction which is vertical to the surface of the living body, the operation processing unit performs

15 computation for determining a temporal change of a value proportional to a root of square sum of change rates of the first-direction magnetic component in second and third directions which cross the first direction and computation for integrating the temporal change of the value over a

20 predetermined interval to determine an integral value, and the display unit displays the integral value.

According to the present invention, (2) in the above biomagnetic field measuring apparatus, the fluxmeters detect temporal changes of components of a biomagnetic

25 field, the magnetic field components being in first and second directions which are parallel to the surface of the living body, the operation processing unit performs computation for determining a temporal change of a value

proportional to a root of square sum of the first-direction and second-direction magnetic components and computation for integrating the temporal change of the value over a predetermined interval to determine an integral value, and

5   the display unit displays the integral value.

Specifically, in the biomagnetic field measuring apparatus in (1) and (2) as above, an isointegral map for connecting points at which the integral values are equal to each other is obtained through interpolation and

10   extrapolation and displayed on the display unit, and the operation processing unit carries out the computation of integrating the temporal change of the value over a predetermined interval to determine the integral value over a plurality of predetermined intervals to determine a

15   plurality of integral values and computation for determining any of the ratio, the sum or the difference between the plurality of integral values, and the plurality of fluxmeters are disposed at equal intervals on the surface of the living body.

20   In the biomagnetic field measuring apparatus of the present invention, components of a magnetic field generated from the heart, that is, a normal component and a tangential component which are respectively vertical and parallel to the chest surface can be displayed

25   simultaneously. In the Cartesian coordinate system (x, y, z), when the direction vertical to the living body surface is assumed to be z axis, the first direction is defined as

z direction, the second direction is defined as x direction and the third direction is defined as y direction. In the polar coordinate system (r, θ, φ), when the direction vertical to the living body surface is assumed to be r

5   axis, the first direction is defined as r direction, the second direction is defined as θ direction and the third direction is defined as φ direction.

Essentially, in the present invention, when the direction vertical to the living body surface is assumed to

10   be z axis of the Cartesian coordinate system (x, y, z) and the plane parallel to the living body surface is assumed to be (x, y) plane, a normal component $B_z(x, y)$ of biomagnetic field vertical to the body surface is detected, and tangential components B_x and B_y of biomagnetic field

15   parallel to the body surface are presumed from change rates of the normal component B_z in the x and y directions, respectively.

According to the present invention, without resort to detection coils for measuring the tangential

20   components B_x and B_y, an isomagnetic map indicative of projection of current distribution upon the two-dimensional (x, y) plane can be obtained, a current source in the living body can be decided from a peak pattern in the isomagnetic map, and (x, y) coordinate positions of a

25   plurality of current dipoles can be known.

The contents of the operation processing carried out by the operation processing unit (a computer such as a personal computer for collecting signals detected by a

plurality of fluxmeters and applying the following operation processing to the collected signals or an electronic circuit in the form of hardware dedicated to the operation processing) will be described.

5   When a plurality of fluxmeters each including a superconducting quantum interference device (SQUID) are used to detect tangential components (parallel to the surface of a living body) $B_x(x, y, t)$ and $B_y(x, y, t)$ of a magnetic field generated from the living body at a position

10   (x, y) on the body surface (where in the Cartesian coordinate system (x, y, z), the plane parallel to the body surface is assumed to be xy plane and the axis vertical to the body surface is assumed to be z), two-dimensional vector magnitude $|B_{xy}(x, y)|$ (hereinafter, $|\ \ |$ represents

15   absolute value) is determined from a root of square sum of the tangential components $B_x(x, y, t)$ and $B_y(x, y, t)$ pursuant to equation (3).

$$|B_{xy}(x, y, t)| = \sqrt{\{(B_x(x, y, t))^2 + (B_y(x, y, t))^2\}} \quad \ldots (3)$$

20   Subsequently, an integral value $I_1(x, y)$ of waveform $|B_{xy}(x, y, t)|$ at each point (x, y) is obtained over a desired interval pursuant to equation (4), an isointegral map for connecting points at which the integral values $I_1(x, y)$ at respective points (x, y) are

25   equal to each other is obtained through interpolation and

extrapolation, and the isointegral map is displayed on the display screen.

$$I_1(x, y) = \int |B_{xy}(x, y, t)| dt \qquad \ldots (4)$$

Hereinafter, presumption of the tangential
5 components B_x and B_y from the measured magnetic field component $B_z(x, y, t)$ vertical to the body surface will be described.

By taking advantage of the fact that the tangential component of biomagnetic field parallel to the
10 body surface best reflects a current flowing through a portion immediately below the body surface and considering the relation between the current flow direction and the magnetic field direction, current distribution in the living body projected upon a two-dimensional plane parallel
15 to the body surface can be surveyed by rotating a tangential vector (B_x, B_y) of the measured magnetic field counterclockwise through 90°. More particularly, where e_x and e_y represent unit vectors in x-axis and y-axis directions, a current vector J indicated by equation (5)
20 can be determined from tangential components B_x and B_y at respective measuring points and can be expressed in terms of distribution (arrow map) of current vector fields at the respective measuring points (x, y).

$$J = - B_y e_x + B_x e_y \qquad \ldots (5)$$

On the other hand, when the normal component B_z of magnetic field vertical to the body surface, an arrow map using a current vector expressed by equation (1) is defined (the first prior art: H. Hosaka and D. Cohen (1976)).

$$J = (\partial B_z/\partial y)\ e_x - (\partial B_z/\partial x)\ e_y \qquad \dots \ (1)$$

Comparing equation (1) with equation (5), the present inventors have found the possibility that equations (6) and (7) stand, that is, the possibility that the tangential components B_x and B_y can be induced from the normal component B_z of the measured magnetic field and have studied in various ways. Results of studies will be described hereunder in greater detail.

$$B_x = -(\partial B_z/\partial x) \qquad \dots \ (6)$$

$$B_y = -(\partial B_z/\partial y) \qquad \dots \ (7)$$

Fig. 1 is a diagram useful for explaining modeling the generation of a magnetic field due to action of the heart (cardiac magnetic field) by a magnetic field generated from a current dipole in a horizontally layered conductor and analyzing the model. In Fig. 1, P designates a horizontally layered conductor having its surface on xy plane of the Cartesian coordinate system (x, y, z), Q designates moment of a current dipole existing at a

position indicated by a position vector r_0 $(x_0,\ y_0,\ z_0)$, and $r(x,\ y,\ z)$ designates a position vector of a measuring point at which magnetic flux density $B(r)$ (magnetic field) is measured.   In the model shown in Fig. 1, a magnetic

5   field $B(r)$ generated outside the horizontally layered conductor P is formulated by Sarvas (literature: Phys. Med. Biol., Vol. 32, No. 1, pp.11-22 (1987)) and is expressed by equation (8).

$$B(r) = \{\mu_0/(4\pi K^2)\}\ \{Q \times a \cdot e_z \nabla K - K e_z \times Q\}$$

10 $\ldots$ (8)

In equation (8), μ_0 designates magnetic permeability of vacuum, e_z designates a unit vector in z-axis direction, "×" designates vector product, "•" designates scalar product, and ∇ designates grad $= (\partial/\partial x,$

15 $\partial/\partial y,\ \partial/\partial z)$.   Then, a is indicated by equation (9), a is indicated by equation (10), K is indicated by equation (11) and ∇K is indicated by equation (12). | |· indicates absolute value.

$$a = r(x,\ y,\ z) - r_0(x_0,\ y_0,\ z_0) \qquad \ldots\ (9)$$

20 $$a = |a| \qquad \ldots\ (10)$$

$$K = a(a + a \cdot e_z) \qquad \ldots\ (11)$$

$$\nabla K = (2 + a^{-1} a \cdot e_z)\ a + a e_z \qquad \ldots\ (12)$$

Tangential components B_x and B_y of the B (r) given by equation (8) which are parallel to the

horizontally layered conductor P and normal component B_z
vertical to the horizontally layered conductor P are given
by equations (13), (14) and (15), respectively.

$$B_x = \{\mu_0/(4\pi K^2)\}$$

5
$$\times [\{Q_x(y-y_0) - Q_y(x-x_0)\} (\nabla K)_x + KQ_y] \quad \ldots (13)$$

$$B_y = \{\mu_0/(4\pi K^2)\}$$

$$\times [\{Q_y(y-y_0) - Q_x(x-x_0)\} (\nabla K)_x + KQ_x] \quad \ldots (14)$$

$$B_z = \{\mu_0/(4\pi K^2)\}$$

$$\times [\{Q_x(y-y_0) - Q_y(x-x_0)\} (\nabla K)_z] \quad \ldots (15)$$

10 On the other hand, a differential in x direction of the
normal component B_z indicated by equation (13) is expressed
by equation (16).

$$\partial B_z/\partial x = \{\mu_0/(4\pi K^2)\} \times [\{Q_x(y-y_0) - Q_y(x-x_0)\}$$
$$\{-2(\nabla K)_z(\nabla K)_x/K - a^{-3}(x-x_0)(z-z_0)^2 + a^{-1}$$

15
$$(x-x_0)\} - (\nabla K)_z Q_y] \quad \ldots (16)$$

Similarly, a differential in y direction of the normal
component B_z is expressed by equation (17).

$$\partial B_z/\partial y = - \{\mu_0/(4\pi K^2)\} \times [\{Q_x(y-y_0) - Q_y(x-x_0)\}$$
$$\{2(\nabla K)_z(\nabla K)_y/K + a^{-3}(y-y_0)(z-z_0)^2 - a^{-1}$$

20
$$(y-y_0)\} + (\nabla K)_z Q_x] \quad \ldots (17)$$

In equations (16) and (17),

$$\alpha = (\nabla K)_z / K \qquad \ldots (18)$$

$$\beta_x = -a^{-3}(x-x_0)(z-z_0)^2 + a^{-1}(x-x_0) \qquad \ldots (19)$$

$$\beta_y = -a^{-3}(y-y_0)(z-z_0)^2 + a^{-1}(y-y_0) \qquad \ldots (20)$$

5   are put, equations (16) and (17) are reduced to equations (21) and (22).

$$\partial B_z/\partial x = -\{\mu_0/(4\pi K^2)\} \times [\{Q_x(y-y_0) - Q_y(x-x_0)\}$$
$$\{2\alpha(\nabla K)_x - \beta_x\} + \alpha K Q_y] \qquad \ldots (21)$$

$$\partial B_z/\partial y = -\{\mu_0/(4\pi K^2)\} \times [\{Q_x(y-y_0) - Q_y(x-x_0)\}$$
10
$$\{2\alpha(\nabla K)_y - \beta_y\} + \alpha K Q_x] \qquad \ldots (22)$$

For simplification, equations (13), (21), (14) and (22) are normalized by a common factor $\{\mu_0/(4\pi K^2)\}$ so as to be reduced to equations (13'), (21'), (14') and (22').

$$B_x = (\nabla K)_x\{Q_x(y-y_0) - Q_y(x-x_0)\} + K Q_y \qquad \ldots (13')$$

15   $\partial B_z/\partial x =$

$$-2\alpha(\nabla K)_x\{Q_x(y-y_0) - Q_y(x-x_0)\} - \alpha K Q_y$$
$$+ \beta_x\{Q_x(y-y_0) - Q_y(x-x_0)\} =$$
$$-2\alpha B_x + \alpha K Q_y + \beta_x\{Q_x(y-y_0) - Q_y(x-x_0)\} \qquad \ldots (21')$$

$$B_y = (\nabla K)_y \{Q_y(y-y_0) - Q_x(x-x_0)\} + KQ_x \quad \ldots (14')$$

$$\partial B_z/\partial y =$$
$$-2\alpha(\nabla K)_y \{Q_x(y-y_0) - Q_y(x-x_0)\} - \alpha KQ_x]$$
$$+\beta_y\{Q_x(y-y_0) - Q_y(x-x_0)\} =$$
$$-2\alpha B_y + \alpha KQ_x + \beta_y\{Q_x(y-y_0) - Q_y(x-x_0)\} \quad \ldots (22')$$

5

As will be seen from equations (13') and (21'), the value of $\partial B_z/\partial x$ equals a value obtained by adding two additional terms to a term equal to $- 2\alpha$ times the tangential component B_x and as will be seen from equations

10   (14') and (22'), the value of $\partial B_z/\partial y$ equals a value obtained by adding two additional terms to a term equal to $- 2\alpha$ time the tangential component B_y.

When moment $Q = (Q_x, Q_y, 0)$, where $Q_x = Q_y = 50$ [nAm], exists at a point $r_0(0, 0, -z_0)$, where $z_0 =$

15   0.05 [m], inside the horizontally layered conductor P as shown in schematic positional relation of Fig. 2, B_x (equation (13)) is compared with $-\partial B_z/\partial x$ (equation (16)). By substituting $x_0 = y_0 = y = 0$ and $Q_0 = 0$ to equations (13) and (16), equations (23) and (24) are obtained.

20   $$B_x(x, 0)$$
$$= \{\mu_0/(4\pi K^2)\} \{- (\nabla K)_x Q_y x + KQ_y\} \quad \ldots (23)$$

$$\partial B_z(x, 0)/\partial x =$$
$$\{\mu_0/(4\pi K^2)\} \{2\alpha(\nabla K)_x Q_y x - \alpha KQ_y - \beta_x Q_y x\}$$
$$\ldots (24)$$

Fig. 3 shows B_x (equation (23)) and $-\partial B_z/\partial x$ (equation (24)) on the horizontally layered conductor P in terms of relative magnetic field magnitude curves C_1 and C_2 which are normalized by maximum values of B_x and $-\partial B_z/\partial x$.

5   More specifically, the curve C_1 represents $B_x(x, 0)/$ $\max|B_x(x, 0)|$ and the curve C_2 represents $\{-\partial B_z(x, 0)/\partial x\}/$ $\max|\partial B_z(x, 0)/\partial x|$. As will be seen from Fig. 3, the distribution of each of the B_x and $-\partial B_z/\partial x$ has a peak at the original ($x = 0$) which is immediately above the

10   existence of the current dipole, indicating that the maximum signals of both the B_x and $-\partial B_z/\partial x$ can be detected when the measuring point is immediately above the point where the current dipole exists. The curve C_2 has a sharper peak than the curve C_1, indicating that the

15   magnetic field distribution due to $-\partial B_z/\partial x$ (equation (16)) has higher spatial resolution than the magnetic field distribution due to B_x (equation (13)).

Magnetic field magnitude curves C_3, C_4 and C_5 depicted in Fig. 4 represent the first, second and third

20   terms of $-\partial B_z(x, 0)/\partial x$, respectively. Gathering from the results shown in Fig. 4, the third term is negligible in relation to the first and second terms, so that the shape of $-\partial B_z(x, 0)/\partial x$ can be deemed to be determined by the first and second terms and equation (24) can be

25   approximated by equation (24').

$$\partial B_z(x, 0)/\partial x =$$
$$(\mu_0/(4\pi K^2)) \ (2\alpha(\nabla K)_x Q_y x - \alpha K Q_y) \qquad \ldots \ (24')$$

Fig. 5 shows curves indicative of magnitude of relative magnetic field obtained by comparing the first term with the second term of each of the equations (13) and (16) after normalization. In Fig. 5, curve C_6 represents {first term of $B_x(x, 0)$}/max$|B_x(x, 0)|$, that is, {$-(\nabla K)_x Q_y x$}/max$|B_x(x, 0)|$, curve C_7 represents {first term of $-\partial B_z(x, 0)/\partial x$}/max$|\partial B_z(x, 0)/\partial x|$, that is, {$-2\alpha(\nabla K)_x Q_y x$}/ max$|\partial B_z(x, 0)/\partial x|$, curve C_8 represents {second term of $B_x(x, 0)$}/max$|B_x(x, 0)|$, that is, {KQ_y}/max$|B_x(x, 0)|$, and curve C_9 represents {second term of $\partial B_z(x, 0)/\partial x$}/ max$|\partial B_z(x, 0)/\partial x|$, that is, {$\alpha KQ_y$}/max$|\partial B_z(x, 0)/\partial x|$.

The results of Fig. 5 show that the distribution of each of the first and second terms of $-\partial B_z(x, 0)/\partial x$ is sharper than the distribution of each of the first and second terms of $B_x(x, 0)$ and the sharpness of the distribution is prescribed by $\alpha = (\nabla K)_z/K$ defined by equation (18).

In Fig. 6, magnetic field curve C_{10} represents $\alpha = (\nabla K)_z/K$, magnetic field curve C_{11} represents -{first term of equation (24)}/{first term of equation (23)}, that is, $2\alpha(\nabla K)_x Q_y x/(\nabla K)_x Q_y x = 2\alpha$, and magnetic field curve C_{12} represents -{second term of equation (24)}/{second term of equation (23)}, that is, $\alpha KQ_y/KQ_y = \alpha$. As shown in Fig. 6, $\alpha = (\nabla K)_z/K$ (curve C_{10}) has a peak point at the original where the current dipole exists, and the peak value is $2/(z-z_0)$. The magnitude of $-\partial B_z(x, 0)/\partial x$ differs from that of $B_x(x, 0)$ by $2/(z-z_0)$ at the peak point. The current

dipole exists at a depth indicated by $(z-z_0)$. It is difficult to determine $(z-z_0)$ from practical measurement of magnetic field. By comparing equations (23) and (24'), equation (25) is obtained.

5

$$-\partial B_z(x, 0)/\partial x$$
$$= \{\mu_0/(4\pi K^2)\} \ \{-2\alpha(\nabla K)_x Q_y x + \alpha K Q_y)$$
$$= 2\alpha B_x(x, 0) - \{\mu_0/(4\pi K)\} \ \alpha Q_y \qquad \ldots (25)$$

Namely, when the second term is smaller than the first term in equation (25), approximate equation (26) is
10   deemed to stand.

$$-\partial B_z(x, 0)/\partial x = 2\alpha B_x(x, 0) \qquad \ldots (26)$$

In generalization, when two additional terms other than $-2\alpha B_x$ is smaller than $-2\alpha B_x$ in equation (21'), approximate equation (27) is deemed to stand.

15      $$\partial B_z/\partial x = -2\alpha B_x \qquad \ldots (27)$$

In the foregoing, the results of studies on the relation between $-\partial B_z/\partial x$ and B_x are described but similarly, this holds true for the relation between $-\partial B_z/\partial y$ and B_y and approximate equation (28) of equation (22') is
20   deemed to stand.

$$\partial B_z/\partial y = -2\alpha B_y \qquad \qquad \ldots \ (28)$$

Hereinafter, the procedure for determining an isomagnetic map by presuming tangential components B_x and B_y from the measured normal component B_z on the assumption

5 that B_x is proportional to $-\partial B_z/\partial x$ and B_y is proportional to $-\partial B_z/\partial y$ pursuant to equations (27) and (28) will be described in greater detail.

When a magnetic field component $B_z(x, y, t)$ vertical to the surface of a living body is detected,

10 change rate $\partial B_z(x, y, t)/\partial x$ in x direction of the $B_z(x, y, t)$ and change rate $\partial B_z(x, y, t)/\partial y$ in y direction of the $B_z(x, y, t)$ are determined and root $S(x, y, t)$ of square sum of the change rates is determined as indicated by equation (33).

15
$$S(x, y, t) = \sqrt{[\{\partial B_z(x, y, t)/\partial x\}^2 + \{\partial B_z(x, y, t)/\partial y\}^2]} \qquad \ldots \ (33)$$

Subsequently, a waveform $St(t, x, y)$ at each point (x, y) is integrated over a desired interval to determine an integral value $I_2(x, y)$ pursuant to equation

20 (34), and then an isointegral map for connecting points at which integral values $I_2(x, y)$ at the respective points (x, y) are equal to each other is obtained through interpolation and extrapolation and the isointegral map is displayed on the display screen.

$$I_2(x, y) = \int |S_t(x, y, t)| dt \qquad \ldots (34)$$

For example, when the heart is an object to be measured, intervals during which respective waves Q, R and S are generated, an interval during which a QRS wave (QRS complex) for generation of Q to S waves is generated and an interval during which a T wave is generated are used for the integration range in equations (4) and (34). Further, a plurality of integration ranges are taken in equations (4) and (34) to determine a plurality of integral values, computation for determining the sum, the difference or the ratio between the integral values is carried out, an isointegral map for connecting points at which the computation results have the same value is determined through interpolation and extrapolation, and the isointegral map is displayed on the display screen. For example, an interval T_1 during which the QRS wave is generated is set as a first integration range and an interval T_2 during which the T wave is generated is set as a second integration range, integral values $I_{1,T1}(x, y)$ and $I_{2,T1}(x, y)$ are determined for the interval T_1 pursuant to equation (4) and integral values $I_{1,T2}(x, y)$ and $I_{2,T2}(x, y)$ are determined for the interval T_2 pursuant to equation (34), and sum $I_{sum}(x, y)$ inclusive of isoweight, difference $I_{dif}(x, y)$ or ratio $r(x, y)$ is determined between the integral values $I_{1,T1}(x, y)$ and and $I_{1,T2}(x, y)$ or between

the integral values $I_{2,T1}(x, y)$ and $I_{2,T2}(x, y)$ pursuant to equations (35) and (36), equations (37) and (38) or equations (39) and (40).

$$I_{sum}(x, y) =$$
$$w_1 \times I_{1,T1}(x, y) + w_2 \times I_{1,T2}(x, y) \qquad \ldots (35)$$

$$I_{sum}(x, y) =$$
$$w_1 \times I_{2,T1}(x, y) + w_2 \times I_{2,T2}(x, y) \qquad \ldots (36)$$

$$I_{dif}(x, y) =$$
$$w_2 \times I_{1,T2}(x, y) - w_1 \times I_{1,T1}(x, y) \qquad \ldots (37)$$

$$I_{dif}(x, y) =$$
$$w_2 \times I_{2,T2}(x, y) - w_1 \times I_{2,T1}(x, y) \qquad \ldots (38)$$

$$r(x, y) = I_{1,T1}(x, y)/I_{1,T2}(x, y) \qquad \ldots (39)$$

$$r(x, y) = I_{2,T1}(x, y)/I_{2,T2}(x, y) \qquad \ldots (40)$$

The results of operations pursuant to equations (35) and (36), equations (37) and (38) and equations (39) and (40) suppress irregularities in isointegral map due to the individual difference and abnormality of living body function due to diseases can be detected.

With the isointegral map obtained in the present invention, states of all living body portions can be

grasped by using the number of maps which is far smaller

than the number of maps required in the prior arts without

analyzing biophenomena by the use of many maps, required in

the prior arts, which indicate states of living body

5 portions at respective time points. Since the peak

position in the isointegral map obtained by using the

tangential component or the normal component of biomagnetic

field coincides with a portion in living body through which

a large amount of current flows, it can be decided from the

10 isointegral map which portion in living body a large amount

of current flows within a desired time zone through. The

biomagnetic field distribution differs greatly individual

by individual but according to the present invention, the

integral value over a desired interval obtained from a

15 waveform representing a temporal change of a component in

each direction of the biomagnetic field is used and

therefore, more quantitative biomagnetic field distribution

can be displayed by using a smaller number of maps and

disease and abnormality of each individual can be grasped

20 objectively and quantitatively.

Further, in the present invention, an isomagnetic

map equivalent to the conventional isomagnetic map based on

B_{xy} can be obtained by measuring only the normal component

B_z without measuring tangential components B_x and B_y

25 through vector measurement. With the conventional

isomagnetic map obtained directly from the normal component

B_z, a plurality of current sources are difficult to

discriminate but in the isomagnetic map of the present
invention, the peak pattern appears immediately above the
current source as in the case of the conventional
isomagnetic map based on B_{xy}, thus bringing about
5 advantages that a plurality of current sources in the
living body can be observed directly and the inverse
problem of analyzing the position and size of the plurality
of current sources can be solved with ease.

To summarize the present invention, reference is
10 made to Fig. 7. More particularly, a biomagnetic field
measuring apparatus of the present invention for measuring
biomagnetic field distribution inside a shield room 1 has
a plurality of fluxmeters each including a superconducting
quantum interference device (SQUID) and operative to detect
15 a biomagnetic field generated from a living body 2 in the
form of a signal, an operation processing unit 8 for
performing the operation processing of the signal, and a
display unit for displaying results of the operation
processing. The fluxmeters detect a temporal change of a
20 vertical magnetic field component representing a component
of the biomagnetic field in a first direction which is
vertical to the surface of the living body, and the
operation processing means performs computation for
determining a temporal change of a value proportional to a
25 root of square sum of change rates of the vertical magnetic
field component in second and third directions which cross
the first direction and computation for determining an

integral value of the temporal change over a predetermined interval, and the display means displays the integral value. Since the quantitative biomagnetic field distribution is displayed by using a small number of maps,
5 disease and abnormality of each individual can be grasped objectively and quantitatively.

Further, in the present invention, an isomagnetic map equivalent to the conventional isomagnetic map based on Bxy can be obtained by measuring only the normal component
10 B_z without measuring the tangential components B_x and B_y through vector measurement and, by setting the number and position of peaks in a pattern of the obtained isomagnetic map to the initial condition, the inverse problem of analyzing the position and size of the current source in the living body can be solved with ease.

15

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is a diagram for explaining analysis of the generation of a cardiac magnetic field by using a model of a magnetic field which is generated from a current
20 dipole in a horizontally layered conductor.

Fig. 2 is a diagram schematically showing the position of moment of a current dipole existing inside the horizontally layered conductor in the present invention.

Fig. 3 is a graph showing relative magnetic field
25 magnitude curves C_1 and C_2 obtained by normalizing B_x and $-\partial B_z/\partial x$ on the horizontally layered conductor by their

maximum values in the present invention.

Fig. 4 is a graph showing magnetic field magnitude curves C_3, C_4 and C_5 representative of the first, second and third terms in $-\partial B_z(x, 0)/\partial x$.

5   Fig. 5 is a graph showing relative magnetic field magnitude curves C_6, C_7, C_8 and C_9 obtained by normalizing the first and second terms of each of the B_x and $\partial B_z/\partial x$ and then comparing the normalized values in the present invention.

10   Fig. 6 is a graph showing relative magnetic field magnitude curves C_{10}, C_{11} and C_{12} representative of $\alpha = (\nabla K)_z/K$, {first term of $-\partial B_z(x, 0)/\partial x$}/{first term of $B_x(x, 0)$} and {second term of $-\partial B_z(x, 0)/\partial x$}/{second term of $B_x(x, 0)$}, respectively, in the present invention.

15   Fig. 7 is a perspective view showing the schematic construction of a biomagnetic field measuring apparatus for cardiac magnetic field measurement practicing the present invention.

Fig. 8 is a perspective view showing the arrangement of magnetic field sensors in the biomagnetic field measuring apparatus for cardiac magnetic field measurement practicing the present invention.

Fig. 9 is a perspective view showing the construction of a single magnetic field sensor for detecting a normal component of a magnetic field in the biomagnetic field measuring apparatus for cardiac magnetic field measurement practicing the present invention.

Fig. 10 is a perspective view showing the construction of a single magnetic field sensor for detecting a tangential component of the magnetic field in the biomagnetic field measuring apparatus for cardiac

5   magnetic field measurement practicing the present invention.

Fig. 11 is a diagram showing the positional relation between the arrangement of magnetic field sensors and the chest of a body in the biomagnetic field measuring

10   apparatus for cardiac magnetic field measurement practicing the present invention.

Figs. 12A, 12B and 12C are diagrams showing temporal waveforms of respective components of a magnetic field generated from the heart of a healthy person and

15   measured at positions of the respective magnetic field sensors in an embodiment of the present invention.

Fig. 13 is a time chart showing tangential components (B_x) in specified two channels measured for the healthy person in an embodiment of the present invention.

20   Figs. 14A, 14B and 14C are an isomagnetic map at the moment of a peak of Q wave, an isomagnetic map at the moment of a peak of R wave and an isomagnetic map at the moment of a peak of S wave, respectively, these maps being obtained from a cardiac magnetic waveform of a healthy

25   person for whom tangential components B_x and B_y of a magnetic field are measured in an embodiment of the present invention.

Fig. 15 is an isointegral map obtained from two

tangential components detected within a time zone during which a QRS wave (QRS complex) of cardiac magnetic waveform of a healthy person appears in an embodiment of the present invention.

Fig. 16 is an isointegral map

$$\left(\sqrt{\left(\frac{\partial B_z}{\partial x}\right)^2 + \left(\frac{\partial B_z}{\partial y}\right)^2} \right)$$ obtained from a normal component

detected within the time zone during which the QRS complex of cardiac magnetic waveform of the healthy person appears in an embodiment of the present invention.

Fig. 17 is an isointegral map obtained from two tangential components detected within a time zone during which a T wave of cardiac magnetic waveform of the healthy person appears in an embodiment of the present invention.

Fig. 18 is a map indicative of the difference obtained by subtracting the isointegral map shown in Fig. 15 from the isointegral map shown in Fig. 17 in an embodiment of the present invention.

Fig. 19 is an isointegral map obtained from two tangential components detected within a time zone during which a QRS complex of cardiac magnetic waveform of a patient of myocardial infarction appears in an embodiment of the present invention.

Fig. 20 is an isointegral map obtained from two tangential components detected within a time zone during which a T wave of cardiac magnetic waveform of the patient of myocardial infarction appears in an embodiment of the

present invention.

Fig. 21 is a map obtained by subtracting the isointegral map shown in Fig. 19 from the isointegral map shown in Fig. 20 in an embodiment of the present invention.

5   Fig. 22 is a diagram showing an example of an output picture on a personal computer of the biomagnetic field measuring apparatus for cardiac magnetic field measurement practicing the present invention.

Fig. 23 is a diagram showing examples of

10 processed images displayed on the display of the biomagnetic field measuring apparatus of the present invention.

Figs. 24A, 24B and 24C are isomagnetic maps at the time that extreme values of Q wave, R wave and S wave

15 of magnetocardiogram (MCG) obtained by measuring normal component B_z in accordance with the conventional method appear.

Figs. 25A, 25B and 25C are isomagnetic maps of B_{xy} obtained by measuring tangential components B_x and B_y

20 of a magnetic field from the heart and synthesizing the tangential components at the time that extreme values of Q wave, R wave and S wave appear in an embodiment of the present invention.

Figs. 26A, 26B and 26C are isomagnetic maps at

25 respective time points obtained pursuant to equations (43) and (44) by using isomagnetic map data of normal component B_z at the time that the extreme values of Q, R and S waves shown in Figs. 24A, 24B and 24C appear in an embodiment of

the present invention.

Fig. 27 is a sectional view showing part of the internal construction of a dewar for encephalic magnetic field measurement of a magnetocephalogram (MEG) system

5   which measures an encephalic magnetic field.

Fig. 28 is a diagram for explaining the relation between a magnetic field component measurable by the MEG system shown in Fig. 27 and the head.

Figs. 29A and 29B are diagrams showing examples

10   of isomagnetic field maps obtained with the MEG system shown in Fig. 27.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

As a coordinate system in biomagnetic field measurement, the Cartesian coordinate system (x, y, z)

15   where magnetic field components are B_x, B_y or B_z and the polar coordinate system (r, θ, ϕ) is used. When an abject to be measured is the heart or the like, the Cartesian coordinate system (x, y, z) having its xy plane corresponding to the wall of the chest is used. When an

20   object to be measured is the brain or the like, the polar coordinate system (r, θ, ϕ), where magnetic field components are B_r, B_θ and B_ϕ, is used because the head has the shape approximating a sphere. In the present embodiment, a magnetic field component vertical to the

25   surface of a living body (normal component) is designated by B_z or B_r and components parallel to the living body

surface (tangential components) are designated by B_x and B_y or B_θ and B_ϕ. Hereinafter, the present embodiment will be described using the Cartesian coordinate system (x, y, z) but when the polar coordinate system (r, θ, φ) is used, B_r,

5 B_θ and B_ϕ may be read in place of B_z, B_x and B_y.

Fig. 7 shows the schematic construction of a biomagnetic field measuring apparatus practicing the present invention. The biomagnetic field measuring apparatus for cardiac magnetic field measurement uses a

10 plurality of magnetic field sensors each including a superconducting quantum interference device (SQUID). For elimination of the influence of environmental magnetic field noise, the cardiac magnetic field measurement is carried out inside a magnetically shielded room 1. An

15 object 2 to be inspected lies on a bed 3 to undergo measurement (the Cartesian coordinate system (x, y, z) as shown in Fig. 1 is set so that its xy plane may coincide with the surface of the bed). A dewar 4 accommodating a plurality of magnetic field sensors each comprised of an

20 integrality of a SQUID and a detection coil connected thereto and being filled with liquid He is disposed above the chest of the inspected object 2. The liquid He is replenished continuously by means of an automatic He introducing device 5 disposed externally of the

25 magnetically shielded room 1.

An output of the magnetic field sensor is supplied to a flux locked loop (FLL) circuit 6 which

delivers a voltage proportional to the magnitude of a magnetic field detected by the detection coil. The FFL circuit cancels a change in biomagnetic field inputted to the SQUID through a feedback coil in order to keep the

5   output of the SQUID constant. By converting current flowing through the feedback coil into voltage, a voltage output proportional to a change in biomagnetic field signal can be obtained. The voltage output is amplified by an amplifier (not shown), its frequency band is selected by a

10   filter circuit 7 and the resulting signal is subjected to AD conversion by means of an AD converter (not shown) so as to be fetched into a computer 8. In the computer 8, various kinds of operation processing are executed, and the results of the operation processing are displayed on the

15   display and delivered to a printer.

As detection coils for detecting tangential components of a magnetic field, two coils having their coil planes oriented to x and y directions, respectively, are used. As a coil for detecting a normal component of the

20   magnetic field, a coil oriented to z direction is used. The arrangement of these magnetic field sensors (20-1 to 20-8, 21-1 to 21-8, 22-1 to 22-8, 23-1 to 23-8, 24-1 to 24-8, 25-1 to 25-8, 26-1 to 26-8 and 27-1 to 27-8) is shown in Fig. 8. The magnetic field sensors stand uprightly inside

25   the dewar from the bottom thereof and the respective sensors are spaced apart equidistantly in x and y directions in order that a distance-dependent change of the

magnetic field can be caught accurately. Here, the inter-sensor distance is 25mm and the number of sensors is 8 × 8 = 64 (channels).

One of the magnetic field sensors arranged in the manner as above is schematically shown in Fig. 9 or 10. A magnetic field sensor shown in Fig. 9 is adapted to detect a component B_z vertical to the body surface and has a coil formed of a superconducting conductor (Nb-Ti conductor) and having its plane oriented to z direction. In this coil, two reverse coils, of which one is a detection coil 10 close to the living body and the other is a reference coil 11 remote from the living body adapted to eliminate external magnetic field noise, are combined to form a first order gradiometer. Exemplarily, the coil diameter is 20 mm and the base line between the coils is 50 mm. The external magnetic field noise is generated from a signal source remote from the living body and can be detected equally by the detection and reference coils. On the other hand, a signal from the living body is detected more strongly by the detection coil 10 close to the living body than by the reference coil 11. Therefore, the detection coil 10 can afford to detect both the signal and the noise but the reference coil 11 can detect only the noise. Accordingly, by taking in the difference between magnetic fields captured by the two coils, measurement can be carried out with a high S/N ratio.

The first order gradiometer is connected to an input coil of a SQUID 12 through a superconducting wiring

line of a package substrate packaging the SQUID 12 to transmit to the SQUID a biomagnetic field detected by the detection coil.

The schematic construction of a magnetic field
5   sensor for detecting tangential components B_x and B_y of the biomagnetic field is illustrated in Fig. 10. The magnetic field sensor uses planar coils, of which detection coil 10' and reference coil 11' are arranged on one plane and detection coil 10" and reference coil 11" are arranged on
10   another plane. The coil size is 20 mm × 20 mm and the base line is 50 mm. Like the coil for normal component, these coils are connected to package substrates of SQUID's 12' and 12". A sensor for magnetic field in x direction, generally designated by reference numeral 13, and a sensor
15   for magnetic field in y direction, generally designated by reference numeral 14, are stuck to two mutually orthogonal surfaces of a support in the form of a prism to form a magnetic field sensor which can detect x and y components. The prisms are arranged in array as shown in Fig. 8.

20   The dewar incorporating the magnetic field sensors is disposed above the chest of the inspected object lying on the bed to detect a magnetic field generated from the heart. Here, the transverse direction of the body is defined as x direction and the longitudinal direction of
25   the body is defined as y direction. The positional relation between the arrangement of the magnetic field sensors (20-1 to 20-8, 21-1 to 21-8, 22-1 to 22-8, 23-1 to

23-8, 24-1 to 24-8, 25-1 to 25-8, 26-1 to 26-8 and 27-1 to

27-8) and the chest 30 is shown in Fig. 11. Biomagnetic

field signals detected under the above positional

relationship are shown in Figs. 12A, 12B and 12C.

5   Figs. 12A, 12B and 12C show temporal changes of a

magnetic field generated from the heart of a healthy person

which are detected by the respective magnetic field sensors

(8 × 8 magnetic field sensors arranged in array), where in

each figure, abscissa of 64 waveforms represents time axis

10   and ordinate represents detected magnetic field magnitude.

Specifically, Fig. 12A shows time (abscissa)-dependent

changes of tangential component B_x, Fig. 12B shows time-

dependent changes of tangential component B_y and Fig. 12C

shows time-dependent changes of tangential component B_z,

15   where illustrated values of the respective components are

normalized by an absolute value of signal magnitude

obtained from a channel which delivers a maximum signal

magnitude.

        Temporal waveforms (time charts) of tangential

20   component (B_x) shown at solid and dotted curves in Fig. 13

are obtained through specified two channels when a healthy

person is measured. Time points at which peaks (extreme

values) of Q, R and S waves are given within a time zone T_1

for appearance of a QRS wave resulting from depolarization

25   of the ventricle of the heart are indicated by t_Q, t_R and

t_S, respectively, in Fig. 13. Further, a time zone for

appearance of a T wave indicative of the process of

repolarization of the heart is indicated by T_2 and a time point at which a peak (extreme value) is given is indicated by t_T.

In Fig. 13, P wave indicates excitation
5 (depolarization) of the atrium, QRS wave consisting of Q, R and S waves indicates excitation (depolarization) of the ventricle and T wave is a gradual deflection which indicates repolarization of the myocardium. The depolarization represents a process in which excitation
10 initially spreads in the muscle and the repolarization represents a process in which the excited muscle returns to a still state.

Figs. 14A, 14B and 14C show isomagnetic maps for connecting points at which magnitudes of cardiac magnetic
15 fields are equal to each other at time points t_Q, t_R and t_S, respectively. Each of the Figs. 14A, 14B and 14C shows two-dimensional vector magnitude distribution indicated by $|B_{xy}(x, y, t)|$ of equation (4) and obtained by synthesizing tangential components B_x and B_y measured at 64 points.
20 Further, in each of the Figs. 14A, 14B and 14C, arrows show two-dimensional vectors on the assumption that current sources at 64 measuring points generate magnetic fields at the respective measuring points. By using the current vectors, the direction and distribution of currents in the
25 heart can be presumed. In each of the Figs. 14A, 14B and 14C, abscissa x and ordinate y indicate coordinates at which the magnetic field sensors are located. Current

flowing in the heart flows right-down direction in the
ventricular septum at the moment of the peak of the Q wave
as shown in Fig. 14A, a large amount of current flows
obliquely downwards in the whole of the left ventricle at
5   the moment of the peak of the R wave as shown in Fig. 14B
and current flows obliquely upwards toward the ventricle
base at the moment of the peak of the S wave, demonstrating
that the depolarization process of the ventricle ends. It
will therefore be seen that the isomagnetic maps of Figs.
10   14A, 14B and 14C make it possible to visualize active
portions and current direction in the heart at respective
time points.

      Fig. 15 shows an isointegral map obtained by
integrating two-dimensional vector magnitudes $|B_{xy}(x, y,$
15   $t)|$ at respective points (x, y), obtained from two
tangential components B_x and B_y detected within the time
zone T_1 during which the QRS wave covering Q to S waves of
the cardiac magnetic waveform appears, pursuant to equation
(4) and connecting points at which integral values are
20   equal to each other. In Fig. 15, x axis and y axis
represent coordinates of the magnetic field sensors
disposed on the body surface and numerical values described
near black circles associated with the respective curves of
the isointegral map indicate integral values owned by the
25   corresponding curves. It will be seen from Fig. 15 that
most of currents flowing in the myocardium within the time
zone of QRS wave take place in the left ventricle in which

the myocardium is thick and the peak position in the isointegral map exactly corresponds to a portion at which the amount of current flowing in the heart is large.

Fig. 16 shows an isointegral map obtained by measuring normal components B_z at respective points (x, y) in connection with the same healthy person for whom data of Fig. 15 is determined from Figs. 12A, 12B and 12C, determining roots $S(x, y)$ pursuant to equation (33), integrating the resulting roots over the time zone T_1 of the QRS wave pursuant to equation (34) and connecting points at which integral values are equal to each other. In Figs. 16 to 21, x axis and y axis represent positional coordinates (in a unit of m) of the magnetic field sensors disposed on the body surface. In Figs. 16 to 21, numerical values described near black circles associated with curves represent integral values owned by the corresponding curves.

It has been found that a pattern of the isointegral map of Fig. 15 determined from the magnetic field tangential components B_x and B_y coincides with a pattern of the isointegral map of Fig. 16 determined from the magnetic field normal component B_z. The coincidence means that equations (6) and (7) or equations (27) and (28) are proven to substantially stand by experimental data.

Fig. 17 shows an isointegral map obtained by integrating two-dimensional vector magnitudes $|B_{xy}(x, y)|$ at respective points (x, y), obtained from two tangential

components B_x and B_y detected within the time zone T_2 of
the T wave in connection with the same healthy person for
whom Fig. 15 is determined, pursuant to equation (4) and
connecting points at which the integral values are equal to
5 each other.

Fig. 18 shows a contour line map which represents
the difference pursuant to equation (37) between the
integral value over the time zone T_2 pursuant to equation
(4) and the integral value over the time zone T_1 for
10 generation of the QRS wave pursuant to equation (4). In
other words, the map of Fig. 18 is obtained by subtracting
the isointegral map shown in Fig. 15 from that shown in
Fig. 17. The time zone T_2 of T wave is longer than the
time zone T_1 of QRS wave. The pattern in Fig. 17 resembles
15 that in Fig. 15. Therefore, the contour line map shown in
Fig. 18 has positive values as a whole. Numerical values
described near black circles associated with curves in
Figs. 17 and 18 each represent the aforementioned
difference value between integral values owned by the
20 corresponding curve.

Next, results of cardiac magnetic field
measurement in a patient of myocardial infarction are shown
in Figs. 19, 20 and 21. Fig. 19 shows an isointegral map
obtained for the time zone T_1 of QRS wave similarly to Fig.
25 15, Fig. 20 shows an isointegral map obtained for the time
zone T_2 of T wave similarly to Fig. 17 and Fig. 21 shows a
contour line map obtained similarly to Fig. 18 to indicate
the difference pursuant to equation (35) between the

integral value over the time zone T_2 of T wave pursuant to equation (4) and the integral value over the time zone T_1 of QRS wave pursuant to equation (4). In other words, Fig. 21 is a map obtained by subtracting the isointegral map

5 shown in Fig. 19 from that shown in Fig. 20. Numerical values described near black circles associated with curves in Figs. 19 and 20 represent integral values owned by the corresponding curves and numerical values described near black circles associated with curves in Fig. 21 represent

10 the difference value between the integral values owned by the corresponding curve.

The isointegral map for the time zone T_1 shown in Fig. 19 has a pattern which slightly differs from those of the isointegral maps shown in Figs. 15 and 16, indicating

15 that a large amount of current has passed through the left ventricle. But the isointegral map for the time zone T_2 shown in Fig. 20 has a pattern which differs from that of the isointegral map for the time zone T_1 shown in Fig. 19, clearly indicating that the pattern of the amount of

20 current flowing through the heart within the time zone T_1 greatly differs from that within the time zone T_2 owing to myocardial infarction. Further, the contour line map shown in Fig. 21 has negative values as a whole and greatly differs from the contour line map of healthy person shown

25 in Fig. 18 having positive values as a whole, clearly indicating that in the patient of myocardial infarction, the current flowing through the heart within the time zone

T_2 suffers from infliction.

As described above, by imaging the magnetic field
magnitude of the heart within the time zones T_1 and T_2, the
healthy state can be discriminated non-invasively with ease

5   from the abnormal state (for example, the myocardial
infarction condition, cardiac ischemic condition or the
like) within a short period of time of less than one minute
without inflicting a pain on the patient. In other words,
early finding and presumption of a diseased portion can be

10 ensured without solving the inverse problem.

Fig. 22 shows an example of a processed image on
the screen of the computer of the biomagnetic field
measuring apparatus. The screen is of the multi-window
type and individual processed images can be displayed on

15 respective windows. While in Figs. 15 to 21 numerical
values are described in association with individual curves
to clarify the level of the magnetic field magnitude and
integral value, coloring is effected on the display in
accordance with the level of the contour line to provide a

20 three-dimensional color display. At the same time, the
time chart (magnetocardiogram) as shown in Fig. 13 as well
as an electrocardiogram can also be displayed to permit
systematic analysis of the heart disease.

Fig. 23 shows examples of processed images

25 displayed on the display of the biomagnetic field measuring
apparatus of the present invention. In Fig. 23, MCG
depicts an example of magnetocardiogram, QRS depicts an

example of a first isomagnetic map obtained pursuant to equation (34) when the integration range is set to the interval T_1 for generation of the QRS wave, T depicts an example of a second isomagnetic map obtained pursuant to

5 equation (34) when the integration range is set to the interval T_2 for generation of the T wave, and (T-QRS) depicts an example of the difference between the first and second isomagnetic maps.

In equations (4) and (34), $I_1(x, y)$ and $I_2(x, y)$

10 can be determined by a simplified method substituting for the integration. More particularly, $I_1(x, y)$ and $I_2(x, y)$ are determined from the following equations (41) to (44) and then, equations (35) to (40) are applied. When tangential components (components parallel to the surface

15 of living body) $Bx(x, y, t)$ and $By(x, y, t)$ of a magnetic field generated from the living body are measured (where in the Cartesian coordinate system (x, y, z), the plane parallel to the body surface is xy plane and the axis vertical to the body surface is z), two-dimensional vector

20 magnitude $|B_{xy}(x, y)|$, where $| |$ represents absolute value, is determined from a root of square sum of the tangential components B_x and B_y pursuant to equation (41).

$$|B_{xy}(x, y, t_0)|$$
$$= \sqrt{\{(B_x(x, y, t_0))^2 + (B_y(x, y, t_0))^2\}}$$

$$\dots \ (41)$$

25

Subsequently, for respective points (x, y),

values $I_1(x, y)$ of a waveform $|B_{xy}(x, y, t_0)|$ at a desired time point are determined pursuant to equation (14), an isointegral map for connecting points at which values of $I_1(x, y)$ at the respective points (x, y) are equal to each other is obtained through interpolation and extrapolation, and the isointegral map is displayed on the display screen.

$$I_1(x, y) = |B_{xy}(x, y, t_0)| \qquad \ldots (42)$$

When a magnetic component $B_z(x, y, t)$ vertical to the living body surface is measured, a change rate $\partial B_z(x, y, t_0)/\partial x$ in x direction of the vertical magnetic component B_z and a change rate $\partial B_z(x, y, t_0)/\partial y$ in $\underline{y}$ direction of the $B_z(x, y, t_0)$ are determined and as shown in equation (43), a root $S(x, y, t)$ of the square sum is determined.

$$S(x, y, t_0) = \sqrt{[\{\partial B_z(x, y, t_0)/\partial x\}^2}$$
$$+ \{\partial B_z(x, y, t_0)/\partial y\}^2] \qquad \ldots (43)$$

Subsequently, for the respective points (x, y), values $I_2(x, y)$ of a waveform $S_{t0}(t_0, x, y)$ at a desired time point are determined pursuant to equation (44), an isointegral map for connecting points at which values of $I_2(x, y)$ are equal to each other at the respective points (x, y) is determined through interpolation and extrapolation, and the isointegral map is displayed on the display screen.

$$I_2(x, y) = |S_{t0}(x, y, t_0)| dt \qquad \dots (44)$$

For example, when the heart is an object to be measured, t_0 in equations (41) to (44) is the time that the maximum value of each wave Q, R or S is given in response

5 to contraction of the ventricle. Further, in equations (41) to (44), a plurality of time points t_0 are set, computation for determining the sum, the difference or the ratio between a plurality of determined values is carried out, an isointegral map for connecting points at which

10 computation results are equal to each other is determined through interpolation and extrapolation, and the isointegral map is displayed on the display screen. In this manner, too, substantially the same results as those obtained by the previously-described method using equations

15 (4) and (34) can be obtained.

Isomagnetic maps at the time that the extreme values of Q, R and S waves in a magnetocardiogram of patient X obtained by measuring a normal component Bz in accordance with the conventional method are illustrated in

20 Figs. 24A, 24B and 24C. In Figs. 24A, 24B and 24C, dotted line indicates an isomagnetic map of a negative magnetic field, solid line indicates an isomagnetic map of a positive magnetic field and a blank arrow indicates the magnitude and direction of a current dipole. In

25 illustrations of the isomagnetic maps of Figs. 24A, 24B and 24C, the blank arrow is superimposed at the position of a

current dipole when a single current source existing in the heart is supposed. At the time that the extreme value of Q wave appears, the current flows in a right-down direction in the ventricular septum as shown in Fig. 24A. A large amount of current flows obliquely downwards in the whole of the left ventricle as shown in Fig. 24B at the time that the extreme value of R wave appears and the current flows obliquely upwards toward the ventricle base as shown in Fig. 24C at the time that the extreme value of S wave appears, indicating that the depolarization process in the ventricle ends.

Isomagnetic maps obtained by measuring tangential components B_x and B_y of a magnetic field generated from the heart of the aforementioned patient X and synthesizing the tangential components pursuant to equations (41) and (42) at the time that the extreme value of each of the Q, R and S waves appears are illustrated in Figs. 25A, 25B and 25C.

A pattern of Fig. 25A substantially coincides with that of Fig. 24A, a pattern of Fig. 25B substantially coincides with that of Fig. 24B and a pattern of Fig. 25C substantially coincides with that of Fig. 24C. But, in the pattern of Fig. 25B obtained at the time that the extreme value of R wave appears, the myocardium acts in a wide region to ensure that a plurality of current sources, not clear in the pattern of Fig. 24B obtained at the moment of the appearance of the extreme value of R wave, can be discriminated easily, making it possible to know that one

current source exists in the left direction and the other current source exists downwards.

Isomagnetic maps at the time that the respective extreme values of Q, R and S waves appear, which are
5   obtained pursuant to equations (43) and (44) by using isomagnetic map data pieces of the normal component B_z at the moment of the appearance of the respective extreme values of Q, R and S waves, are illustrated in Figs. 26A, 26B and 26C. From the results shown in Figs. 26A, 26B and
10   26C, a plurality of current sources, which are hardly discriminated by the use of the isomagnetic maps of normal component B_z shown in Figs. 24A, 24B and 24C or the arrow map based on equation (1), can be discriminated. It will be appreciated that patterns of Figs. 26A, 26B and 26C are
15   equivalent to those (isomagnetic maps of B_{xy} obtained by synthesizing the tangential components B_x and B_y) shown in Figs. 25A, 25B and 25C. This means that equations (6) and (7) or equations (27) and (28) are proven to substantially stand by practical experimental data.

20   In each of the Figs. 24A to 26C, abscissa x and ordinate y represent positional coordinates of the magnetic field sensors disposed on the living body surface.

While in the foregoing the present invention has been described by way of example of cardiac magnetic field
25   measurement, the present invention can obviously be applied to even encephalic magnetic field measurement for obtaining a magnetoencephalogram (MEG).

Fig. 27 shows, in sectional view form, part of
the internal construction of a dewar for encephalic
magnetic field measurement of an encephalic magnetic field
measuring system for measurement of an encephalic magnetic
5 field. When an encephalic magnetic field is measured, an
object to be inspected is the head which differs from the
chest by taking the form of a sphere and therefore, as
shown in Fig. 27, the bottom surface of a dewar 102 for
measuring head incorporating SQUID fluxmeters 103-1, 103-2,
10 , 103-N is made to take the form of a semi-sphere which
covers a head 100. The SQUID fluxmeters 103-1, 103-2, ...,
103-N are disposed radially along the inner surface of the
head measuring dewar 102 and the fore end surface (magnetic
field measuring surface) of each SQUID fluxmeter is
15 disposed substantially in parallel to the tangential plane
of the semi-spherical surface. The radius of the semi-
sphere is set on the assumption that the brain of the head
is a sphere having its center which substantially coincides
with the center of the semi-sphere, amounting up to about
20 10cm which permits measurement for even grown-up persons.
A thermal radiation shield 104 is arranged inside the head
measuring dewar 102 and the top of the head measuring dewar
is sealingly closed by a top plate 105. Signals detected
by the SQUID fluxmeters 103-1, ..., 103-N are taken out to
25 the outside of the head measuring dewar through signal
lines 106-1, ..., 106-N.

Fig. 28 is useful to explain the relation between
the magnetic component measurable by the encephalic

magnetic field measuring system shown in Fig. 27 and the
head. The component of an encephalic magnetic field B
measurable by a SQUID fluxmeter disposed radially above the
head at one of a plurality of positions, O', is a component
5   Br in r direction (normal component) on the polar
coordinate system (r, θ, ϕ) having its origin at O. In
Fig. 28, components B_θ and B_ϕ indicate tangential
components parallel to the head surface and the origin is
the center of a sphere on the assumption that the brain
10 take the form of the sphere. An electrical stimulation is
applied, as a bodily sense, to the right middle finger, the
normal component Br is detected by the encephalic magnetic
field measuring system shown in Fig. 27 and an isomagnetic
map at the time that a brain wave appearing about 100msec
15 after the application of the electrical stimulation is
maximized is obtained. Figs. 29A and 29B show examples of
the isomagnetic map obtained with the encephalic magnetic
field measuring system shown in Fig. 27. The isomagnetic
map of normal component B_r shown in Fig. 29A is obtained in
20 accordance with the conventional method and the isomagnetic
map of Fig. 29B is obtained by using the following equation
(45) according to the present invention. Like a map
depicted on a globe, the isomagnetic map indicates the
magnitude distribution of encephalic magnetic field
25 depicted on the surface of the sphere approximating the
brain.

$$S\ (\theta,\ \phi,\ t)$$

$$= \sqrt{\ \{(\partial B_r(t)/\partial\theta)^2\ +\ (\partial B_r(t)/\partial\phi)^2\}} \qquad \ldots\ (45)$$

In the isomagnetic map shown in Fig. 29A, the current dipole when a single current source existing in the brain is supposed is positioned at a blank arrow superimposed on the illustration. In Fig. 29A, dotted line represents an isomagnetic map of a negative magnetic field, solid line represents an isomagnetic map of a positive magnetic field and the blank arrow indicates the magnitude and direction of current dipole. It can be directly visualized with ease that the current source (represented by the current dipole indicated by the blank arrow) conventionally presumed on the basis of the isomagnetic map of normal component B_r shown in Fig. 29A takes place in correspondence to a peak position A in the isomagnetic map shown in Fig. 29B. The other part of encephalic magnetic field measuring system, which is not shown in Fig. 27, is constructed essentially identically to that of the biomagnetic field measuring apparatus shown in Fig. 7.

As methods of analyzing the magnetic field source by using the isomagnetic maps concerning cardiac magnetic field and encephalic magnetic field obtained through the various methods of the present invention described so far, various kinds of algorithm for solving the inverse problem are conceivable. In simplified algorithm used frequently in practical applications, a single or two or so current

dipoles are assumed as the magnetic field source,
positional coordinates at which these current dipoles exist
are supposed desirably as the initial condition, and on the
assumption that the current dipoles existing at the

5   individual positional coordinates generate magnetic fields
indicated by the Biot-Savart's formula, magnetic fields at
actual magnetic field measuring points (x, y) are
calculated. An evaluation function pursuant to equation
(17) which is indicated by the difference between

10   calculated magnetic field $B_c(x, y)$ and actually measured
magnetic field $V_m(x, y)$ is calculated where m = 1, 2, , M
and the total number of measuring points at which the
magnetic fields are actually measured is represented by M,
and the minimum value of evaluation function L is

15   analytically determined by changing the positional
coordinates of the individual current dipoles. In equation
(46), G represents a constant, n_s represents a unit vector
in normal or z direction, and addition symbol Σ represents
the addition concerning m = 1, 2, ,M.

20
$$L = \Sigma\{V_m(x, y) - G([B_c(x, y)] \cdot n_s)\}^2 \quad \ldots \quad (46)$$

With the method based on equation (46), however,
an instance occurs where the results of magnetic field
source analysis do not converge to the minimum value when a
wide measuring region of magnetic field is analyzed. In

25   the present invention, the initial conditions for the

position and number of dipoles in the course of calculation of the evaluation function L are so predetermined that the peak position in the isomagnetic map based on equation (4), (34) or (44) is the position of dipole and the number of

5 peaks in the isomagnetic map is the number of dipoles. By solving the evaluation function L under the thus predetermined initial conditions, results of the magnetic field source analysis can converge without fail. By designating respective peak positions on the isomagnetic

10 maps concerning cardiac magnetic field and encephalic magnetic field based on equation (4), (34) or (44), coordinates of the respective peak positions and the number thereof can be inputted automatically, as the initial values, to the apparatus and the evaluation function L can

15 be solved to provide converging results of magnetic field source analysis.

Accordingly, in contrast to the conventional setting of initial values effected in trail and error fashion, the initial values can be determined substantially

20 definitely with ease on the basis of data of the isomagnetic map obtained as a result of measurement and the inverse problem can be solved efficiently and more accurately.

In each of the figures depicting the isomagnetic

25 maps used in the foregoing description, the right side of the body is illustrated on the left side of the drawing and the left side of the body is illustrated on the right side

of the drawing in accordance with the common rule practiced in the field of medical treatment.